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DYNAMIC RANGE CONSIDERATIONS IN NARROWBAND AND WIDEBAND SUPERHETERODYNE SURVEILLANCE RECEIVERS (U)

by

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ABSTRACT

This report examines the dynamic range performance of narrowband and wideband superheterodyne surveillance receivers. A theoretical review of parameters indicative of the dynamic range performance of each type of receiver is presented. It is seen that for a narrowband superheterodyne receiver, the dynamic range performance can be specified using a parameter based on a single tone at the input. For a wideband superheterodyne receiver, one or more two tone dynamic range parameters are needed. These two tone dynamic range parameters are then used to predict the dynamic range performance of a wideband superheterodyne surveillance receiver currently being built for DREO. Some anticipated dynamic range problems specific to this system are discussed.

RESUME

Ce rapport traite de la plage d'opération linéaire de récepteurs de surveillance superhétérodynes à bande passante étroite ou large et contient une revue théorique des paramètres déterminant la plage d'opération linéaire de chaque type de récepteur. On note que la plage d'opération linéaire d'un récepteur superhétérodyne à bande passante étroite peut être déterminée par un paramètre dépendant d'un signal d'entrée d'une seule tonalité. Cependant, il faut utiliser un ou plusieurs paramètres dépendant de deux tonalités pour prédire la plage d'opération linéaire d'un récepteur superhétérodyne à large bande passante. Ces paramètres dépendant de deux tonalités sont alors utilisés pour prédire la plage d'opération linéaire d'un récepteur de surveillance superhétérodyne à large bande passante en voie de construction au CRDO. Quelques problèmes reliés à la plage d'opération linéaire de ce système particulier sont anticipés et discutés.

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1.0 INTRODUCTION

The purpose of a communications intercept receiver system is to monitor the frequency spectrum over a pre-defined range and provide as much information as possible about any signals present. To do this, the system must first perform a spectral search; also called spectral surveillance. The search provides an indication of signal activity, usually in the form of a panoramic display. Following the search, and at the discretion of the operator, a detailed analysis is performed on one or more of the signals discovered.

Signal analysis can imply many things. It can be a simple demodulation of any message contained in the signal, or it can be a detailed spectral analysis of the signal. Analysis can also involve more exotic processing such as call sign recognition, language recognition and translation, or signal fingerprinting. The difference between the analysis mode and surveillance mode is that during the analysis mode, the receiver is tuned only to one signal and the processing is performed only over the bandwidth of that signal. In surveillance mode, the processing is performed over the entire frequency range of interest, although not necessarily on all frequencies at once.

Conventional intercept receivers are generally of a scanning narrowband superheterodyne configuration. Spectral search is accomplished by converting signals to a fixed intermediate frequency (IF) around which is centered a bandpass filter. Processing performed after this IF filter (post processing) consists of energy detection and threshold comparison. The IF filter defines the detection bandwidth of the receiver. Since the post processing offers no enhancement of the resolution, the search resolution is limited to the detection bandwidth. Analysis is performed by disabling the scan and tuning the IF filter to the signal of interest. The bandwidth of the IF filter may have to be changed in order to match the signal bandwidth. The post processor for the analysis mode will also be different.

When operated in surveillance mode, narrowband superheterodyne receivers offer high sensitivity and a large dynamic range, but there is a trade-off between resolution and probability of interception. Definite improvements in the probability of interception can be obtained by processing a wider bandwidth at the IF stage and using either parallelism or high speed digital processing to enhance resolution. Depending on the type of post processing employed, the detection bandwidth can be many times larger than the resolution obtained. If the detection bandwidth is larger than the resolution, the receiver is referred to as a wideband superheterodyne receiver.

Defence Research Establishment Ottawa (DREO) is currently having developed under contract a Digital Quadrature Detector which will digitize the "Switched IF Output" (4 MHz BW) of a Watkins Johnson 8617B receiver and provide the in-phase (I) and quadrature (Q) components of the IF signal as output. A processor which will perform a subsequent complex Fast Fourier Transform (FFT), using the I and Q signals, is to be developed under a

different contract. The WJ8617B Receiver, Digital Quadrature Detector, and FFT post processor will form a wideband superheterodyne surveillance receiver system which should offer a significant improvement in the probability of interception for signals in the 20 - 1100 MHz range. This range is limited by the range of the WJ8617B receiver. The system, illustrated in Fig. 1, will have the capability of performing a 4096 point (4K) FFT in 20 msec. It will have two modes of operation. In the coarse search mode, the FFT will be performed on the entire 4 MHz bandwidth yielding a resolution of approximately 1.5 kHz. In the fine search mode, the FFT is to be performed over a 200 kHz bandwidth, resulting in a resolution of approximately 50 Hz. A scanning narrowband superheterodyne receiver requires approximately 2 seconds to perform an identical coarse search and at least 80 seconds to perform the same fine search. The improvement in search speed, achieved through wideband processing, increases the probability of interception of the spectral search.

The improvement in probability of interception however, will be obtained at the expense of a degradation in dynamic range performance. This report will examine the dynamic range performance of both wideband and narrowband superheterodyne surveillance receivers. The analysis phase of operation will not be considered since large dynamic range is not a primary concern in the analysis phase. It will be shown that in general, dynamic range performance suffers when a wider IF bandwidth is processed unless special consideration is given to the design of the receiver front end. In addition, it will be shown that the applicability of certain dynamic range parameters as an indication of the receiver performance depends on the type of receiver used, as well as on the type of post processing employed. Finally, anticipated dynamic range problems specific to the surveillance system under development will be examined.

2.0 SPECTRAL SEARCH

2.1 Introduction

One of the primary functions of an intercept receiver is to perform a spectral search. Spectral search or surveillance is a relatively low resolution spectral analysis performed over the entire frequency range of interest. It is done to obtain an indication of signal activity in order to assess channel usage. A detailed spectral analysis of each signal is not required during surveillance; only an indication of the spectral locations of the signals. The frequency resolution used for the search depends on the signal environment and the band in which the surveillance takes place. Normally, the resolution desired in a search is equal to the channel width allocation for a certain band. For example, in the VHF band (30 - 88 MHz) channel allocation is 25 kHz. However, a worst case scenario would allow for the existence of two continuous wave - on off keyed (CW-OOK) signals at adjacent frequencies. Separation of these two signals would require a resolution of 100 Hz. In general then, the resolution with which spectral surveillance should be conducted is equal to the highest resolution possible, to a maximum of 100 Hz, that is consistent with a rapid search of the entire range of interest.

A spectral search consists of two operations: interception and detection.

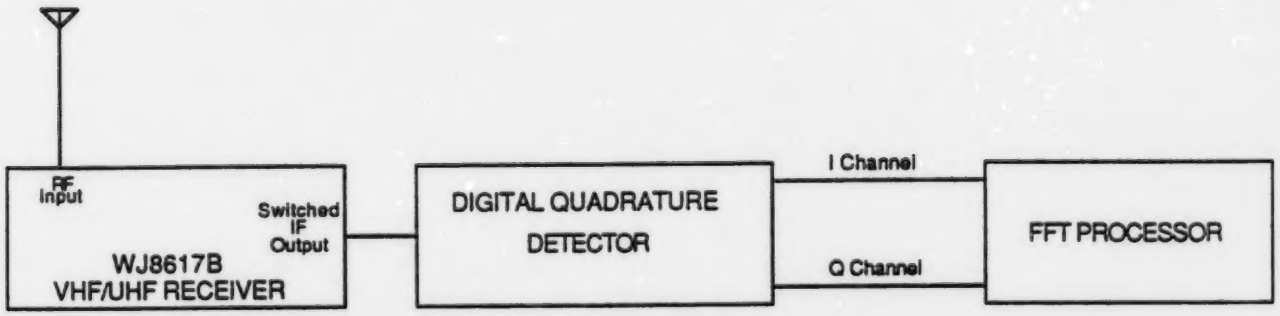

Fig . 1
Wideband Superheterodyne Surveillance System

2.2 Interception

The interception of signals involves the tuning of the receiver detection band to a certain frequency at a time coincident with signal activity at that frequency. The detection band is the range of frequencies over which the receiver is capable of simultaneously detecting all signals present. The detection bandwidth is defined by the bandwidth of the IF filter immediately preceding the post processor in a surveillance receiver. It is the bandwidth over which the signal processing in the post processor is restricted [1].

If the frequency range of interest is large, the surveillance receiver must either have a wide detection bandwidth, enabling it to simultaneously evaluate all signals present within the range of interest, or it must have the ability to rapidly scan a narrower detection band through the entire range of interest.

The probability of interception (PoI) is the probability that any given signal located at an arbitrary position within the signal environment will appear within the detection band at some point during the search. Note that the occurrence of signal activity within the detection band (signal interception) does not guarantee that the signal will be detected. Signal detection depends on the amount of time the signal is within the detection band.

If the detection bandwidth covers the frequency range of interest, the probability of interception can be specified in terms of two parameters: a data acquisition time and a processing time. The data acquisition time is the time required to collect the amount of data required to evaluate signal activity to the desired resolution. The processing time is the time required to perform the necessary post processing. Both parameters depend on the resolution desired, and on the type of post processing performed.

A staring surveillance receiver can simultaneously detect all signals present within a pre-defined range of interest. Both the data acquisition and processing times are negligible. An example of this type of surveillance receiver is an acousto-optic spectrum analyser. Since the entire frequency range of interest is covered at all times, the probability of interception is 100% (Fig. 2).

If the processing time is not negligible, and the receiver is unable to collect data during the processing, it is blind to changes which occur during processing. Rather than being a true staring receiver, this type of receiver "blinks" at the spectrum (Fig. 3). A 100% probability of interception is assured only if the processing time is less than the minimum signal duration. A receiver in which the spectral surveillance is performed using an FFT could represent a blinking receiver if the processing time exceeds the data acquisition time. In this case, the processing time is the time required to calculate the FFT and perform any windowing or averaging on the data. The data acquisition time is the time required to collect the necessary number of samples. If the processing time does not exceed the data acquisition time, double buffering of the input samples will allow the FFT to be calculated without the loss of any data. The receiver will then stare at the band over which the FFT is being performed.

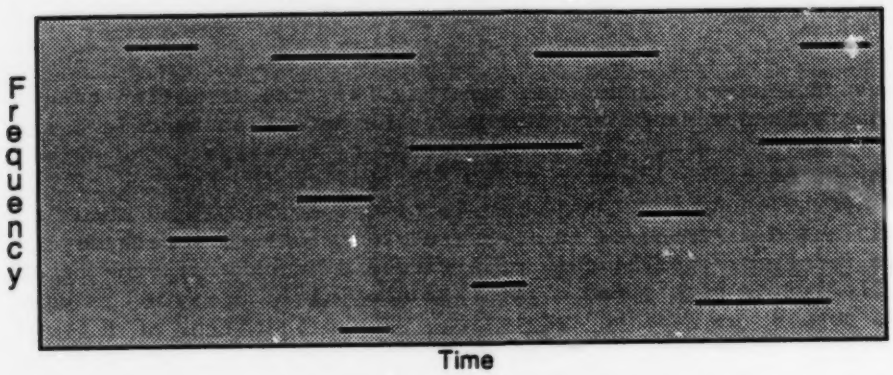

Fig. 2
Staring Receiver

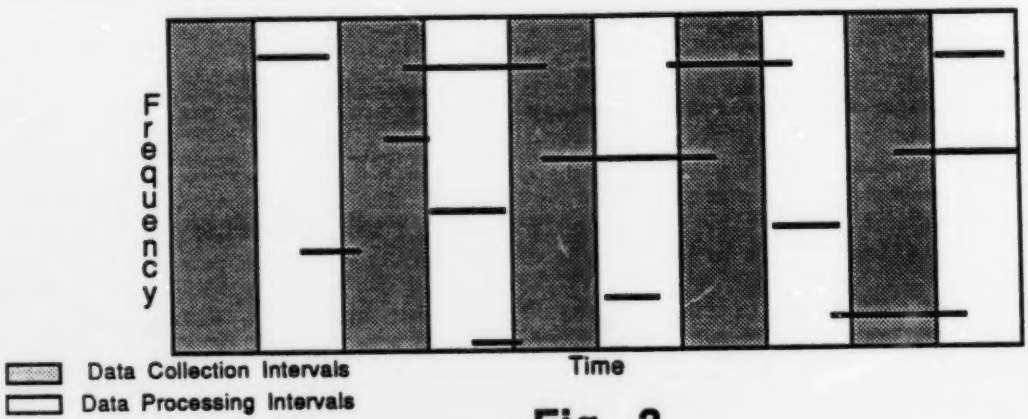

Fig. 3
Blinking Receiver

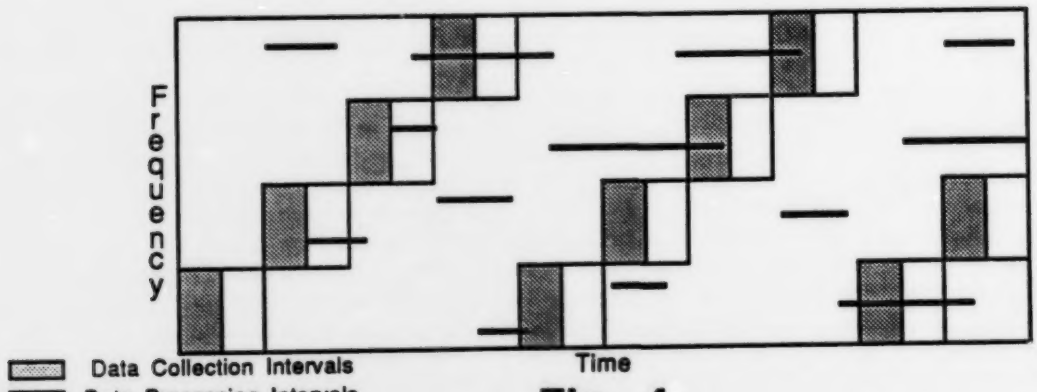

Fig. 4
Scanning Receiver

* Shaded Areas Indicate Complete Coverage

In a scanning surveillance receiver (Fig. 4), the detection bandwidth is less than the frequency range of interest. The detection band is scanned through the range of interest to achieve complete coverage. The detection bandwidth may be equal to the resolution desired, as in the case of a narrowband superheterodyne surveillance receiver, or it may be much larger than the resolution desired, as in the case of a wideband superheterodyne surveillance receiver. In the case of a wideband superheterodyne receiver, either parallelism or high speed digital processing is used in the post processor to obtain the desired resolution. The probability of interception for a scanning receiver is a function of three parameters: the detection bandwidth, the data acquisition time and the processing time. For a scanning superheterodyne receiver, the maximum scanning speed is given by:

$$S_{max} = \frac{B_{det}^2}{n + B_{det}\,[T_p + T_d]} \qquad (1)$$

S_{max} - maximum scanning speed (Hz/sec)
B_{det} - detection bandwidth (Hz)
T_d - data acquisition time (sec)
T_p - processing time (sec)
n - constant indicating the detection filter settling time (settling time = n/B_{det})

As can be seen from equation 1, if the data acquisition and processing times are negligible, the scanning speed is proportional to the square of the detection bandwidth. This is due to the settling time of the filter defining the detection band. Typically n is 3 or 4, however for high Q filters it may be more. 100% probability of interception is guaranteed only if the time to scan the entire frequency range of interest is less than the minimum signal duration.

2.3 Detection

Given that an interception has occurred and a valid signal is within the detection bandwidth, a decision as to the presence of that signal must be made. This operation is referred to as signal detection. Signal interception does not guarantee signal detection. However, a signal must be intercepted before it can be detected. Ideally, detection can be performed by measuring the energy within the detection band and comparing this measurement to a threshold defined when the signal is absent. When noise is present in the detection band however, errors in the detection decision can be made. A signal can be present but the receiver may fail to detect it, or a detection may be indicated when in fact a valid signal is not present in the detection band. The figures of merit quantifying the performance of a receiver in view of these two possible errors are the probability of missed signal given interception (PoM/I) and the probability of false alarm (PFA) respectively. An equivalent way of expressing PoM/I is to give the probability of detection given interception (PoD/I):

$$PoD/I = 1 - PoM/I \quad (2)$$

PoD/I - probability of detection given interception
PoM/I - probability of missed signal given interception

PoD/I and PFA are functions of the processing time, the data acquisition time, and the signal to noise ratio of any intercepted signal. PoD/I can be made arbitrarily high if enough data is collected and processed. PFA can be similarly made arbitrarily low.

The overall probability of detection is given by:

$$PoD = (PoD/I)(PoI) \quad (3)$$

PoD - probability of detection
PoD/I - probability of detection given interception
PoI - probability of interception

From equation 3 it can be seen that efforts made to improve the probability of detection given interception, such as averaging, may in fact degrade the overall probability of detection since the increased data acquisition and processing time incurred as a result can degrade the probability of interception.

3.0 SCANNING NARROWBAND SUPERHETERODYNE SURVEILLANCE RECEIVERS

3.1 Introduction

A scanning narrowband superheterodyne surveillance receiver (Fig. 5) intercepts signals by converting them to a fixed intermediate frequency (IF) around which a narrowband filter (the IF filter) is centered. This has the same effect as physically sweeping the IF filter through the spectrum. The conversion from RF to the final IF may be done in two or even three steps to reduce image products and spurious signals. The first IF value may depend on the RF band selected, but the final IF is constant regardless of the frequency to which the receiver is tuned. The final IF filter is called the detection filter and defines the detection bandwidth of the receiver. Following the detection filter is an amplifier, energy detector and threshold comparator. Most of the gain from the RF to IF stage is provided by the amplifier following the detection filter.

Strictly speaking the term "superheterodyne" applies only to those type of receivers where the intermediate frequency is less than the received carrier frequency, but greater than the post detection signal frequency [2]. Other receivers which use frequency conversion are called heterodyne receivers. However, common usage of the term "superheterodyne" has widened the definition to include heterodyne receivers which have an up-conversion stage. The post detection signal is usually at baseband and is called the video signal.

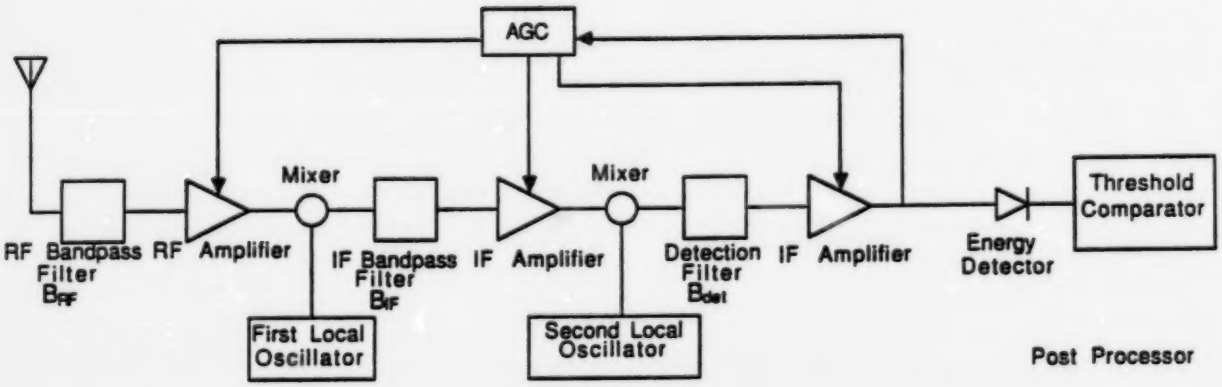

Fig. 5
Narrowband Superheterodyne Receiver

The post processor employed in a narrowband scanning superheterodyne surveillance receiver consists of a simple energy detector followed by a threshold comparator. Since this arrangement offers no enhancement of the search resolution, the resolution that is achieved is equal to the detection bandwidth. Two signals with a spectral separation less than the detection bandwidth cannot be separated by the narrowband superheterodyne receiver. They are treated as a single signal with the video signal indicating the combined signal strength.

The operation of a scanning surveillance receiver was discussed briefly in section 2. Interception occurs when the detection filter is tuned to a certain frequency at a time coincident with signal activity at that frequency. Detection occurs when the signal energy measured within the detection filter exceeds a certain threshold.

In the case of a scanning narrowband superheterodyne receiver, both the processing and the data collection times are negligible. It is the settling time of the detection filter which imposes a limitation on the time to scan a particular frequency range of interest. The maximum scanning speed is proportional to the square of the detection bandwidth. Since resolution is equal to the detection bandwidth in the case of a scanning narrowband superheterodyne receiver, the maximum scanning speed is proportional to the square of the resolution bandwidth. Doubling the search resolution by halving the detection bandwidth results in a factor of four decrease in the scanning speed of the detection filter. Since the probability of interception is proportional to the scanning speed, the probability of interception decreases with increased resolution. It should be noted however, that decreasing the resolution (increasing the detection bandwidth) decreases the signal to noise ratio (SNR) within the detection bandwidth. This can have a detrimental effect on the probability of detection given interception.

3.2 Dynamic Range of Narrowband Superheterodyne Receivers

3.2.1 Sensitivity

Sensitivity of the narrowband superheterodyne surveillance receiver is a measure of the minimum signal strength that can be detected. It is a subjective parameter, usually based on the signal to noise ratio of the video signal. It is also a function of an acceptable probability of detection and probability of false alarm.

For the purposes of this paper, the sensitivity is defined in terms of a minimum discernible signal (MDS) at the input to the energy detector. The MDS is defined as that RF input signal power which results in a (S+N)/N ratio of 3 dB at the output of the IF amplifier following the detection filter. It is given by: (Appendix I)

$$MDS = 10 \log [1000\ kT\ B_{det}] + F \qquad (4)$$

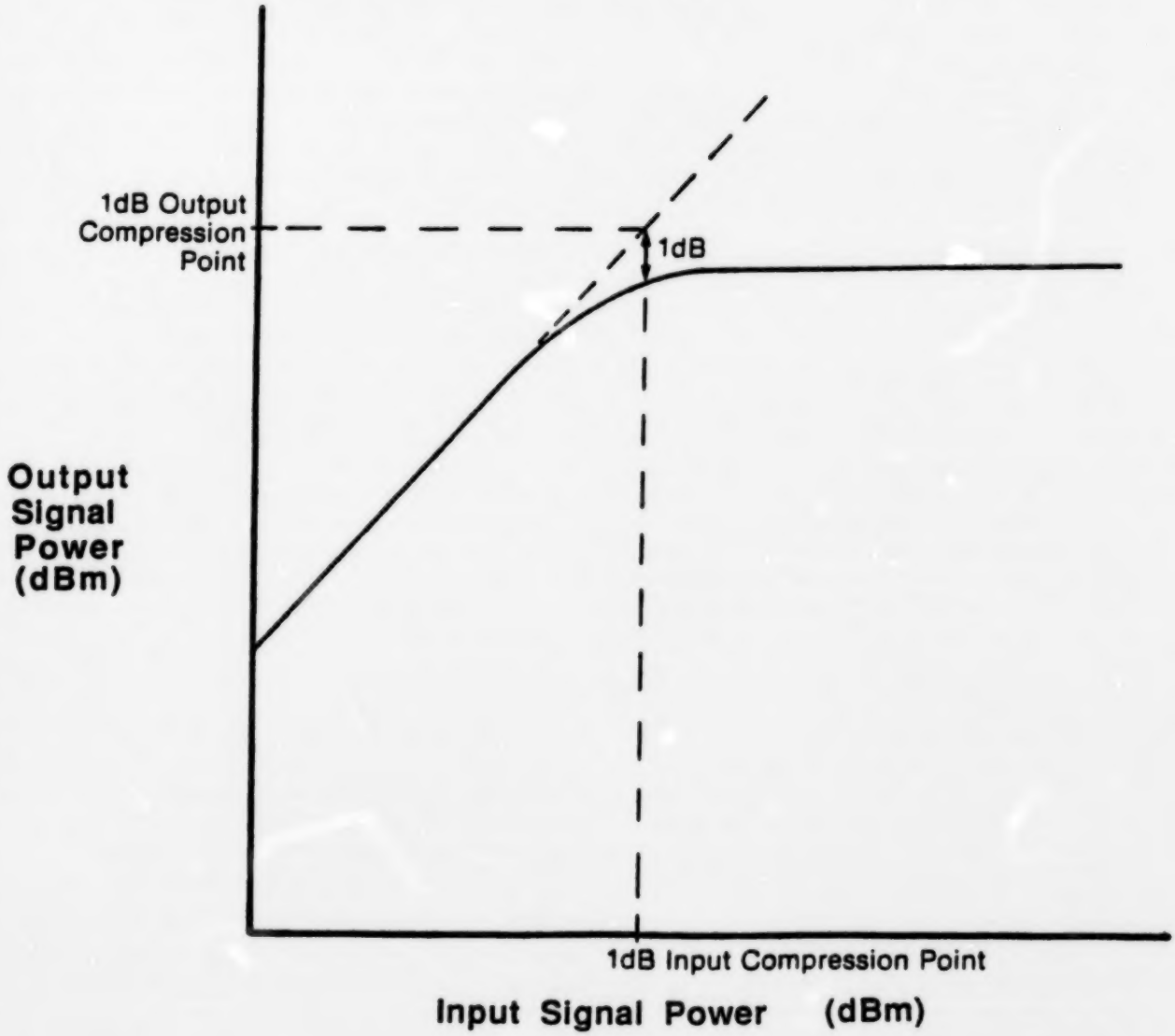

Fig. 6
Typical Input-Output Signal Power Transfer Function For RF to IF Stage Without AGC

Note: The factor of 1000 references the noise power to 1 mW

MDS - Minimum Discernible Signal (dBm)
F - Receiver Noise Figure (dB)
k - Boltzman's constant 1.374×10^{-23} Joules/Kelvin
T - Ambient Temperature (usually 290 K)
Bdet - Effective Noise Bandwidth of the Detection Filter (Hz) (Approximately equal to the 3 dB bandwidth)

It must be emphasized that this definition is arbitrary in that the probability of detection, false alarm rates, and signal observation times have not been considered. It has simply been assumed that for an input (S+N)/N ratio of 3 dB, the energy detector will give acceptable performance. If this is not the case, the definition must be refined to reflect the new requirements.

3.2.2 1 dB Compression Point

The maximum signal which can be detected by a narrowband superheterodyne receiver is generally taken to be the input signal strength at which the distortion of the output becomes unacceptable. The input-output signal power transfer function of the RF and IF amplifier stages, assuming no Automatic Gain Control (AGC), is as shown in Fig. 6. There are two regions of operation, the linear region and the compression region. In the linear region, a 1 dB increase in the input signal strength results in a 1 dB increase in the output signal strength. In the compression region, this is not the case. The point at which the output deviates from the projected linear response by 1 dB is the 1 dB compression point and, when referred to the input, is generally taken to be the upper limit to the range of signals the receiver is capable of processing [3].

3.2.3 Single Tone Dynamic Range

The single tone dynamic range is given by the difference between the 1 dB input compression point (in dBm) and the MDS (in dBm). This definition however is gain dependent, since the 1 dB input compression point is inversely proportional to gain. As a result, it is difficult to compare amplifiers having different gains. For example, tests performed on the WJ8617B receiver, with AGC disabled, indicate that for an IF bandwidth of 6.4 kHz and an RF to IF gain of approximately 80 dB, the single tone dynamic range is 35 dB. For an RF to IF gain of 60 dB, the single tone dynamic range increases to 55 dB. As can be seen, the sum of the dynamic range and the RF to IF gain remains constant.

3.2.4 Enhancement of Single Tone Dynamic Range Through The Use Of AGC

One way to improve the single tone dynamic range is through the use of an automatic gain control (AGC). This device monitors signal strength at some point in the receiver and adjusts gain levels accordingly to ensure that all amplifiers are operated in their linear regions. The input-output transfer function of the RF to IF stage varies with the input signal level (Fig. 7). Although the effective transfer function is very similar to that of Fig. 6, the amplifiers do not compress within the AGC control range.

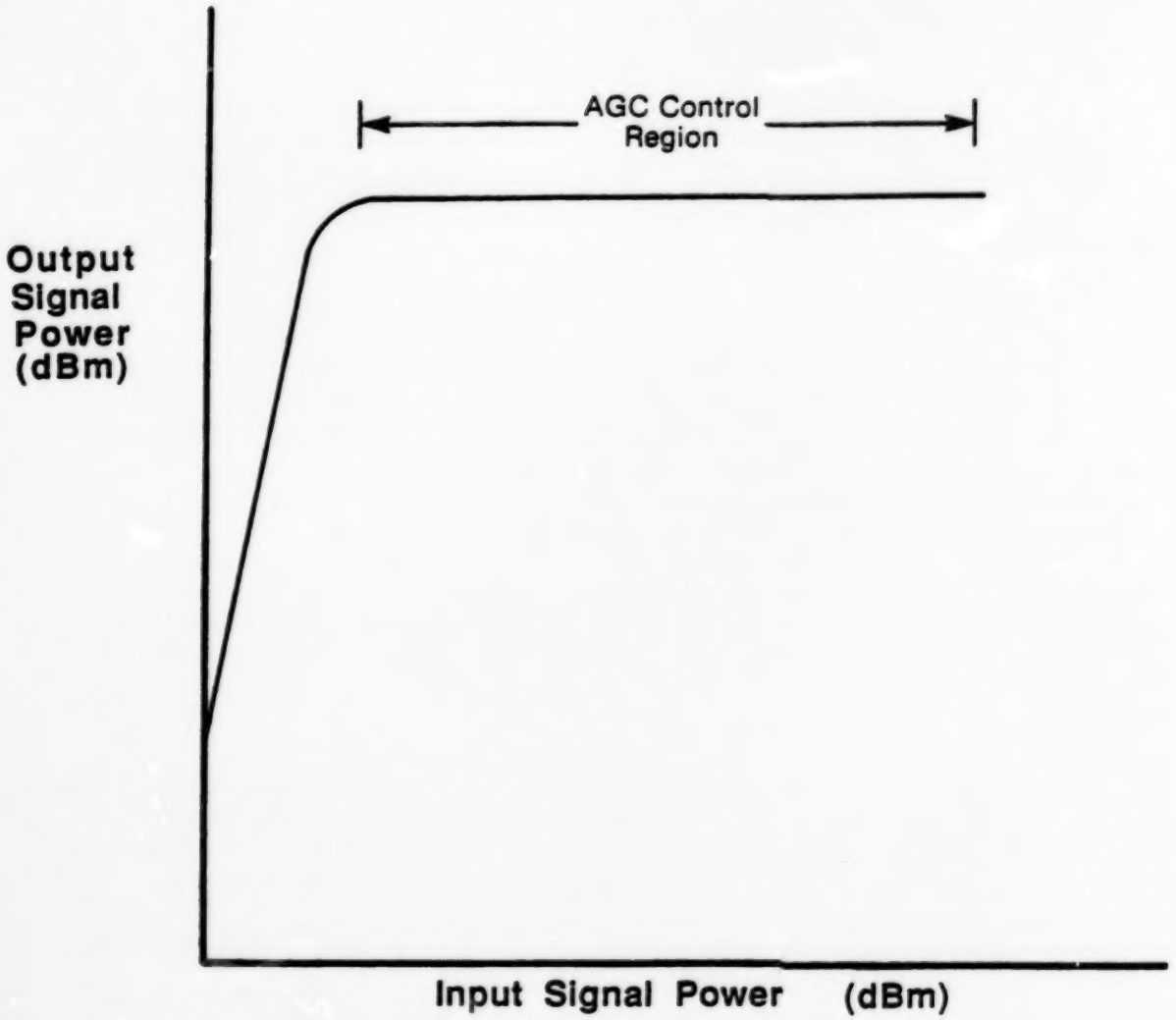

Fig. 7
Typical Input-Output Signal Power Transfer Function For RF to IF Stage With AGC

There are also two time constants associated with the gain adjustment in Fig. 7. The attack time constant represents the time constant with which the AGC responds to a rapid increase in signal strength. The decay time indicates the AGC response to a rapid decrease in signal level. Most AGCs are of the fast attack/slow decay type. A fast attack time is chosen so that the gain is adjusted according to the signal peaks. A slow decay time is chosen in order to preserve any amplitude modulation which may be on the signal. Assuming that the time constants have been chosen correctly, AGC increases the single tone dynamic range significantly since it effectively increases the one dB input compression point. As a result a larger range of signals can be used as input. On the WJ8617B receiver, the AGC controlled single tone dynamic range, assuming a resolution of 6.4 kHz, is in excess of 100 dB. Measurements indicate that the attack time constant is approximately 3 msec and the decay time constant is approximately 11 msec. Amplitude modulation as low as 200 Hz is passed undistorted from the RF input to the IF stage.

One of the disadvantages of AGC is that it causes a degradation in receiver noise figure when input signal strengths exceed a certain threshold (Appendix II). On the WJ8617B receiver, this degradation is shown in Fig. 8 for an IF bandwidth of 6.4 kHz. Even if the AGC is not applied directly to the front end amplifier, it will eventually have an effect on the receiver noise figure.

4.0 WIDEBAND SUPERHETERODYNE SURVEILLANCE RECEIVERS

4.1 Introduction

A wideband superheterodyne receiver (Fig. 9) is similar to its narrowband counterpart. However, in the wideband case, the detection bandwidth is larger than the ultimate frequency resolution. In most cases it is many times larger. In practice this type of receiver can be implemented using the front end of an existing narrowband superheterodyne receiver and further processing the IF output at a wider bandwidth. The WJ8617B receiver, for example, provides a "Switched IF Output" port having selectable IF bandwidths from 6.4 kHz to 4 MHz. It also provides a "Wideband IF Output" port having a bandwidth of 8 MHz.

Post processing in a wideband superheterodyne receiver must not only detect signals, but it must also enhance the resolution. As a result, the processing is generally more complex than in the narrowband case. The processor may consist of a channelized arrangement comprised of a bank of narrowband filters, each followed by an energy detector and threshold comparator, or it may consist of an A/D converter followed by FFT hardware. The detection in the case of the FFT processor is performed either in hardware or software based on the FFT. With both arrangements there is a processing gain associated with the post processing. The processing gain is an enhancement of signal to noise ratio and plays a major role in the dynamic range performance of the receiver.

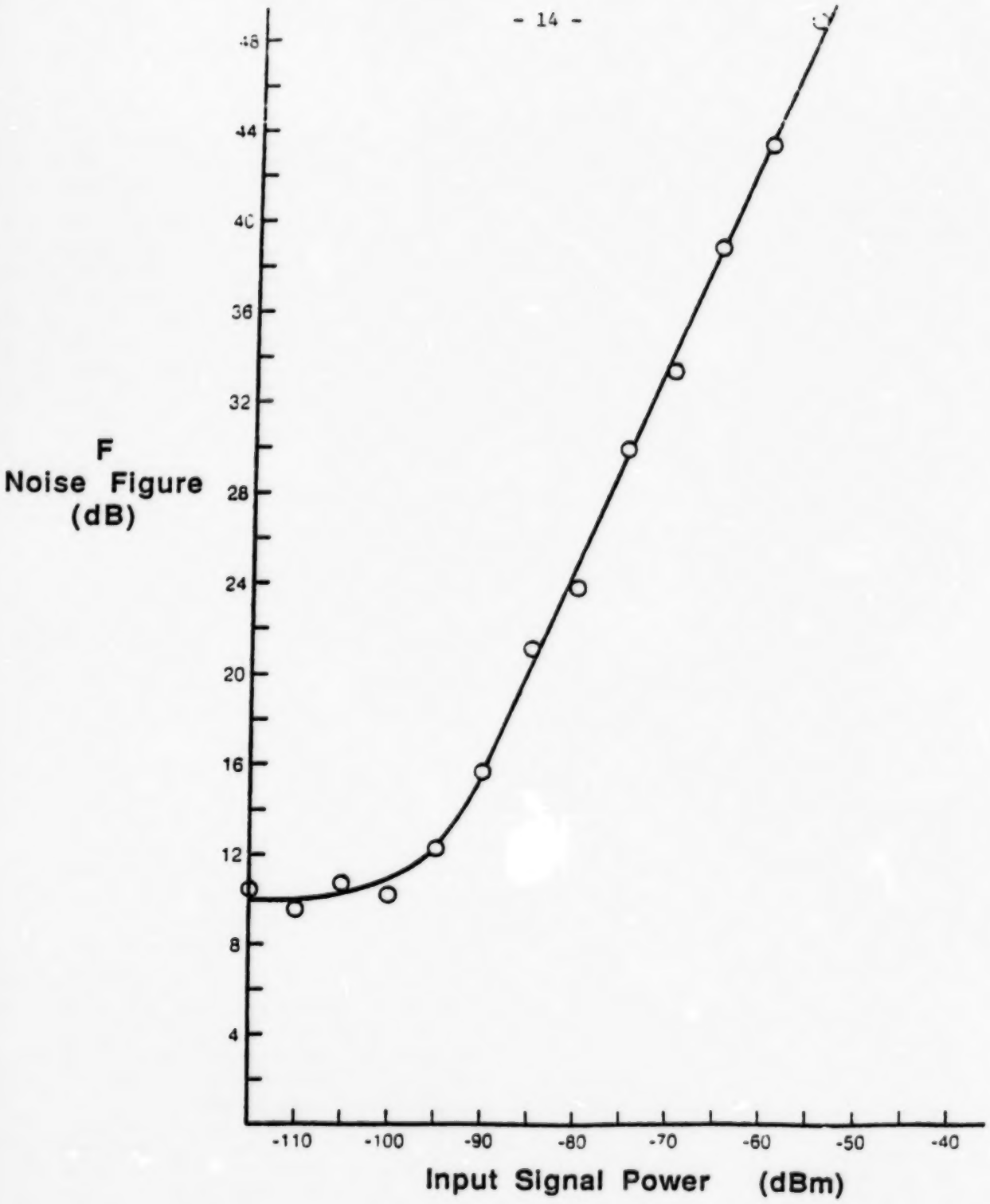

Fig. 8

Receiver Noise Figure Vs Input Signal Power For WJ8617B Receiver 6.4 kHz BW, AGC On

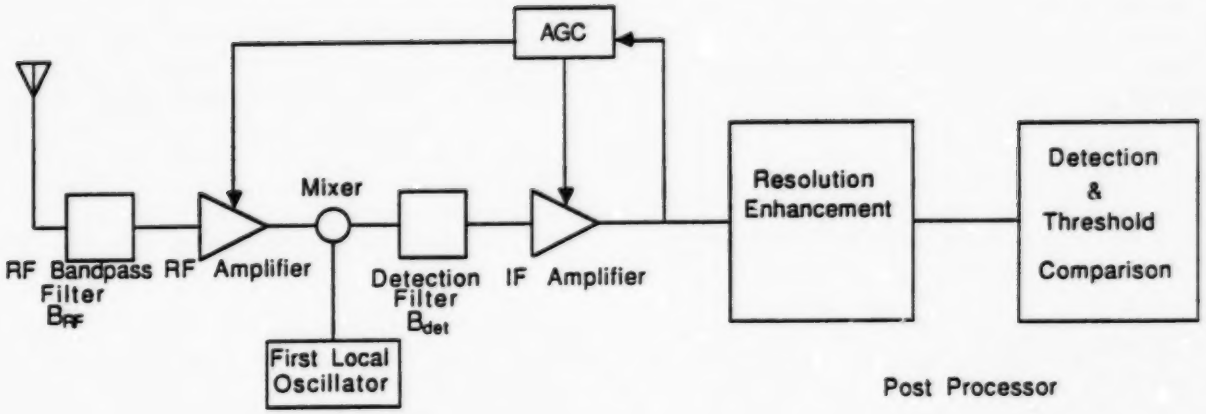

Fig. 9
Wideband Superheterodyne Receiver

For the wideband superheterodyne receiver, the single tone dynamic range parameter discussed previously is not adequate to specify the overall dynamic range performance. Since many signals of interest can appear simultaneously within the detection band and be subsequently amplified, intermodulation products may be generated. Therefore, a multi-tone dynamic range parameter is needed. One type of two tone dynamic range parameter may be based on the intermodulation response of the receiver to two tones appearing simultaneously within the detection bandwidth. A second two tone dynamic range parameter may be defined in terms of the ultimate signal to noise ratio after resolution enhancement.

4.2 Intermodulation

4.2.1 Intermodulation Products and Third Order Intercept

Even in the linear region of operation of an amplifier (discussed in section 3.2.2) performance is not ideal. The input-output characteristic in this region is in fact a complex function which can only be approximated by a linear function. Two tones, of frequencies f1 and f2, applied simultaneously to the input of a perfectly linear amplifier, would result in an output consisting only of frequencies f1 and f2. In a real amplifier however, the output consists of all frequencies $|mf1+nf2|$, where m and n can be any integer. All output products except the fundamental products (m=1&n=0 and n=1&m=0) are called intermodulation products or intermods. The amplitude of these intermodulation products is an indication of the nonlinearity of the amplifier. A higher level of intermods indicates a greater nonlinearity. The sum of $|m|+|n|$ gives the order of the intermodulation product. The attenuation of intermodulation terms, relative to the fundamental output terms, increases with their order.

In the case of two tones applied to the RF input of a wideband superheterodyne receiver, intermods are generated in all mixer and amplifier stages. However, if the gain in the final IF amplifier is high, the intermodulation performance of the receiver is governed primarily by the performance of the final IF amplifier [4]. The final IF signal contains the two original tones as well as many of the intermodulation products. The intermodulation products which are of the most concern are those where $|m|+|n|=3$; the third order products. Second order products ($|m|+|n|=2$) are usually out of the IF band of interest, and higher order products are usually attenuated significantly. For example, consider two tones of equal amplitude separated by 25 kHz placed at the RF input of a WJ8617B receiver. The "Switched IF Output" using an IF bandwidth of 4 MHz is as shown in Fig. 10. The third order products can be clearly seen.

For a 1 dB increase in each of the input tones, fundamental outputs will increase by 1 dB. Third order products will increase by 3 dB (Fig. 11). The theoretical point where third order products are equal in power to the fundamental outputs is called the third order intercept point of the receiver. It should be noted that due to compression of both the fundamental and third order curves, an amplifier will never operate at this point. The third order intercept point is given by: (Appendix III)

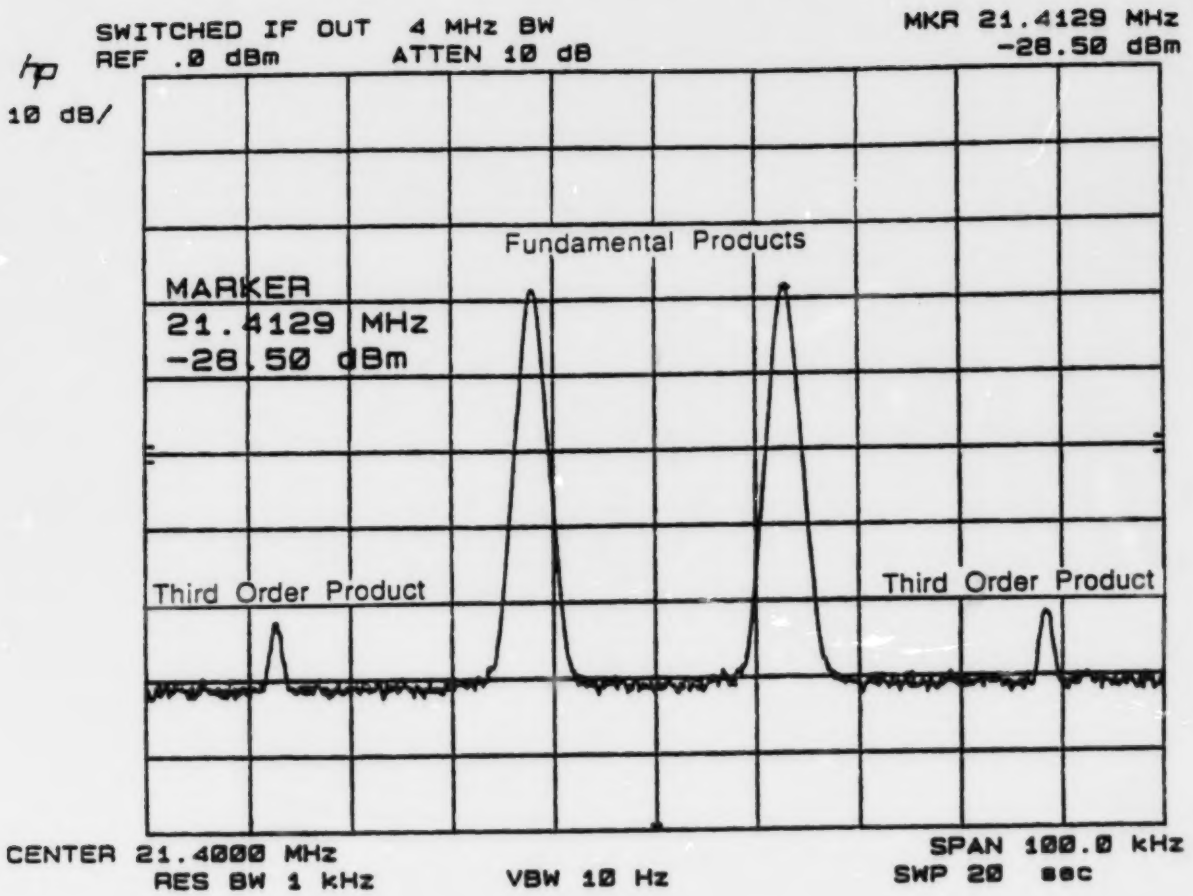

Fig. 10
Intermodulation Products Seen At "Switched IF Output" Of WJ8617B Receiver 4 MHz BW

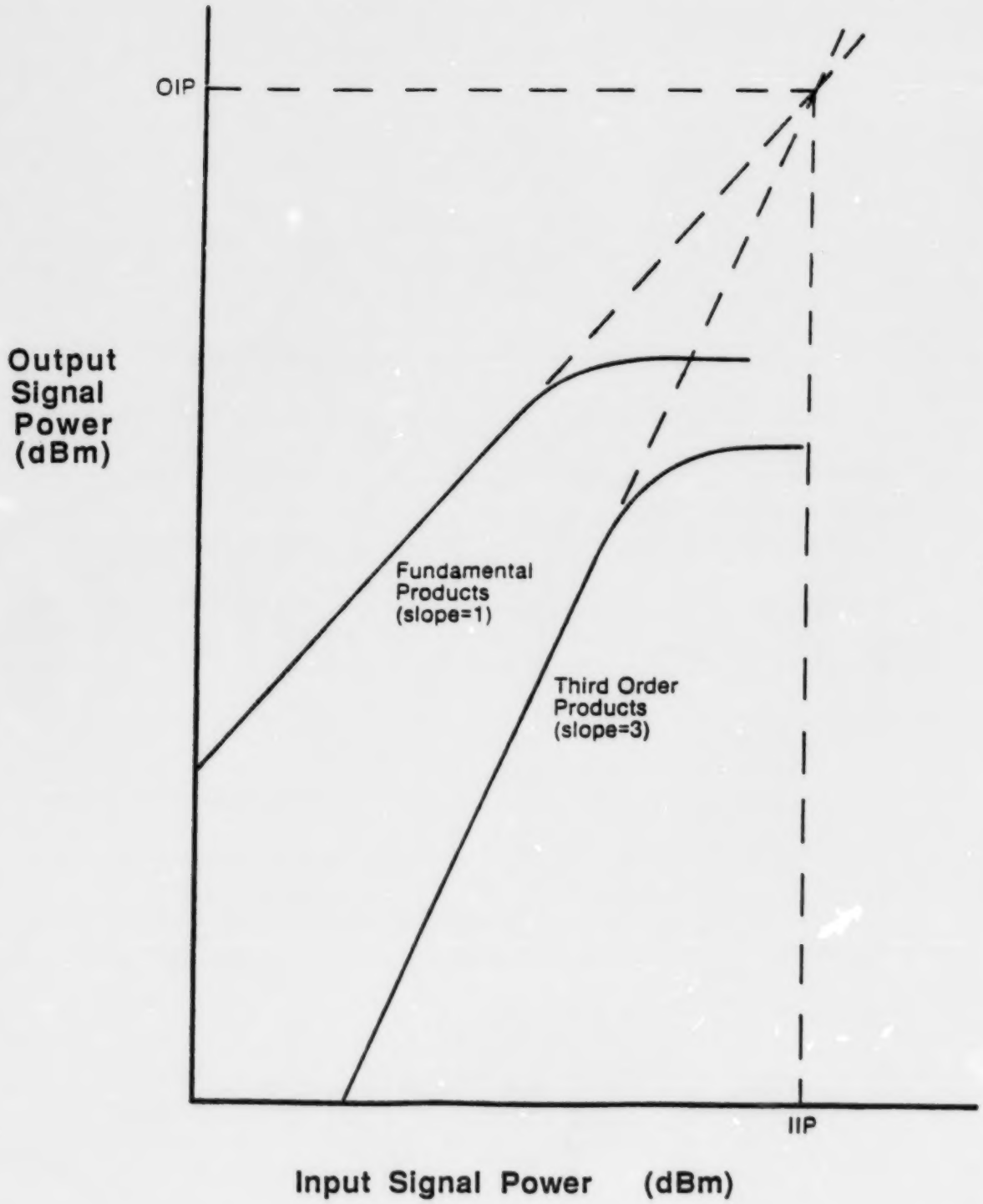

Fig. 11
Input-Output Signal Power Transfer Function For Fundamental and Third Order Products

$$IIP = \frac{R}{2} + S_i \qquad (5.a)$$

$$OIP = \frac{R}{2} + G + S_i \qquad (5.b)$$

IIP - third order intercept point referenced to the input (dBm)
OIP - third order intercept point referenced to the output (dBm)
R - suppression of third order products relative to the fundamental output (dB)
S_i - signal strength of each of the two RF input tones at which R is measured (dBm)
G - RF to IF gain (dB)

In a variable gain amplifier, the effect of increasing the gain is to shift the curves in Fig. 11 to the left. An upward shift is impossible since the compression region for each curve defines the upper limit of the output for the fundamental product and the third order product. Since a variation in gain will cause a shift in the curves either to the right or left, it can be seen that the OIP remains constant regardless of gain. The fact that OIP is independent of gain is not immediately obvious from equation 5.b. There is however, a one to one relationship between S_i and G. As the gain increases one dB, S_i decreases by the same amount. The result is a constant OIP. IIP is indirectly dependent on the gain because of this same one to one relationship between S_i and G.

4.2.2 Intermodulation Products in Narrowband Superheterodyne Receivers

Intermodulation products also occur in the narrowband superheterodyne receiver if two tones appear simultaneously within the detection bandwidth. The nonlinearity of the IF amplifier following the detection filter will generate these products. However, since the energy detection is done only over the bandwidth of the detection filter, any intermods generated within the bandwidth of the detection filter add very little to the energy within. For example, intermods which are 30 dB below the fundamental products add only 0.1% to the energy within the detection bandwidth. A relative suppression of 30 dB represents severe intermodulation distortion. In practice the energy added as a result of in band intermods will be much less. Intermodulation products generated outside the detection filter have no effect on the energy detection.

If the intermodulation products are generated before the detection filter they can be processed as valid signals if the detection filter is tuned to them. Providing most of the RF to IF gain after the detection filter in a narrowband superheterodyne receiver reduces this problem.

Since in a narrowband superheterodyne receiver, energy detection is done only over the bandwidth of the detection filter, and most of the gain is provided after the detection filter, the effects of intermodulation products in a narrowband superheterodyne receiver are not as pronounced as in a wideband superheterodyne receiver. Therefore, the two tone parameters about to be introduced do not apply to a narrowband superheterodyne receiver and the best indication of the dynamic range performance for that type of receiver is the single tone dynamic range.

4.3 Dynamic Range Performance of Wideband Superheterodyne Receivers

4.3.1 Sensitivity

The Minimum Discernible Signal (MDS) for a wideband superheterodyne receiver is very similar to the MDS for the narrowband superheterodyne receiver. In the wideband case however, the processing gain of the post processor must be considered. As mentioned previously, the post processing may consist of a channelized arrangement comprised of a bank of narrowband filters and energy detectors, or an A/D converter and FFT hardware. In the case of a bank of narrowband resolution filters the processing gain is given by:

$$P = 10 \log \left[\frac{B_{det}}{B_{res}} \right] \tag{6}$$

P - Processing Gain (dB)
B_{res} - Resolution Bandwidth (Hz)
B_{det} - Detection Bandwidth (Hz)

In the case of an FFT processor, the exact processing gain is defined by such factors as the transform length and type of windowing used. However, the FFT can be conceptually viewed as a bank of narrowband filters. Therefore as a first approximation, the processing gain given by equation 6 will also apply to an FFT post processor. If the MDS is again defined as the input signal which causes a 3 dB (S+N)/N ratio at the detector input, it becomes

$$MDS = 10 \log [1000\ kT\ B_{det}] + F - P \tag{7}$$

MDS - Minimum Discernible Signal (dBm)
F - Receiver noise Figure (dB)
k - Boltzman's constant 1.374×10^{-23} Joules/Kelvin
T - Ambient Temperature (usually 290 K)
B_{det} - Effective Noise Bandwidth of the Detection Filter (Hz)

By substituting equation 6 into equation 7, MDS can be written directly in terms of the resolution.

$$MDS = 10 \log [1000\ kT\ B_{res}] + F \tag{8}$$

4.3.2 Spurious Free Dynamic Range

The dynamic range over which internally generated third order products (referred to the input) remain below the MDS is called the Spurious Free Dynamic Range (SFDR) [5]. It can be related to the third order intercept point by (Appendix IV)

$$SFDR = 2/3(IIP-MDS) \tag{9}$$

SFDR - Spurious Free Dynamic Range (dB)
IIP - Third Order Intercept Point (dB)
MDS - Minimum Discernible Signal (equ 7)

Note that IIP is a function of the gain, making SFDR a gain dependent parameter.

Any third order product which is above the MDS, when referred to the input, will be processed as a valid signal. The output of the post processor will indicate the presence of a signal when in fact one does not exist. This false signal indication, caused by the generation of a third order product within the receiver, is called a spurious signal. To ensure that spurious signals do not occur, the range of receiver input signals must be constrained to be within the SFDR.

From equations 8 and 9 it can be seen that the SFDR can be increased by increasing the resolution. This method of increasing the SFDR is very costly in terms of either added complexity in the post processor or a decrease in the probability of interception. For example, if the resolution bandwidth was halved, doubling the resolution, at best a 2 dB increase in SFDR would be obtained. This small gain in SFDR would probably not warrant the added post processor requirements. In the case of a bank of narrowband filters, twice the number of filters having half the bandwidth would be needed. In the case of an FFT post processor, twice the number of points would have to be taken in the transform. This would demand a longer processing time which would in turn decrease the probability of interception for the receiver.

The second way of increasing the SFDR is by increasing the IIP of the receiver front end. If most of the gain is provided by the last IF amplifier, the IIP point of the front end will be governed primarily by the IIP of the last amplifier. Simultaneously satisfying the requirements of a wide bandwidth, high IIP, and large gain is very difficult in the design of analog amplifiers.

Problems in the SFDR unique to the WJ8617B are discussed in section 5.

4.3.3 Instantaneous Dynamic Range

Even if the spurious free dynamic range is not a limiting factor in the performance of a wideband superheterodyne receiver, a second two tone dynamic range must be examined. It is determined by the receiver noise figure and any post processing gain. It will be called the instantaneous dynamic range (IDR). The IDR represents a wideband superheterodyne receiver's ability to process two signals of significantly different power levels. It is a measure of the ultimate signal-to-noise ratio possible at the output of a receiver with a fixed processing gain in the post processor.

Consider two tones of different amplitudes separated by 25 kHz placed at the RF input of a WJ8617B receiver with the "Switched IF Output" set to 4 MHz. The IF output, viewed with a processing gain of approximately 36 dB, appears as shown in Fig. 12. Fig. 12 is the output of an HP8568 Spectrum Analyser measuring the "Switched IF Output" with a resolution bandwidth of 1 kHz. The processing gain is calculated using equation 6 by substituting 4 MHz for B_{det} and 1 kHz for B_{det}. This processing gain simulated the processing gain of a post processor in the wideband superheterodyne receiver.

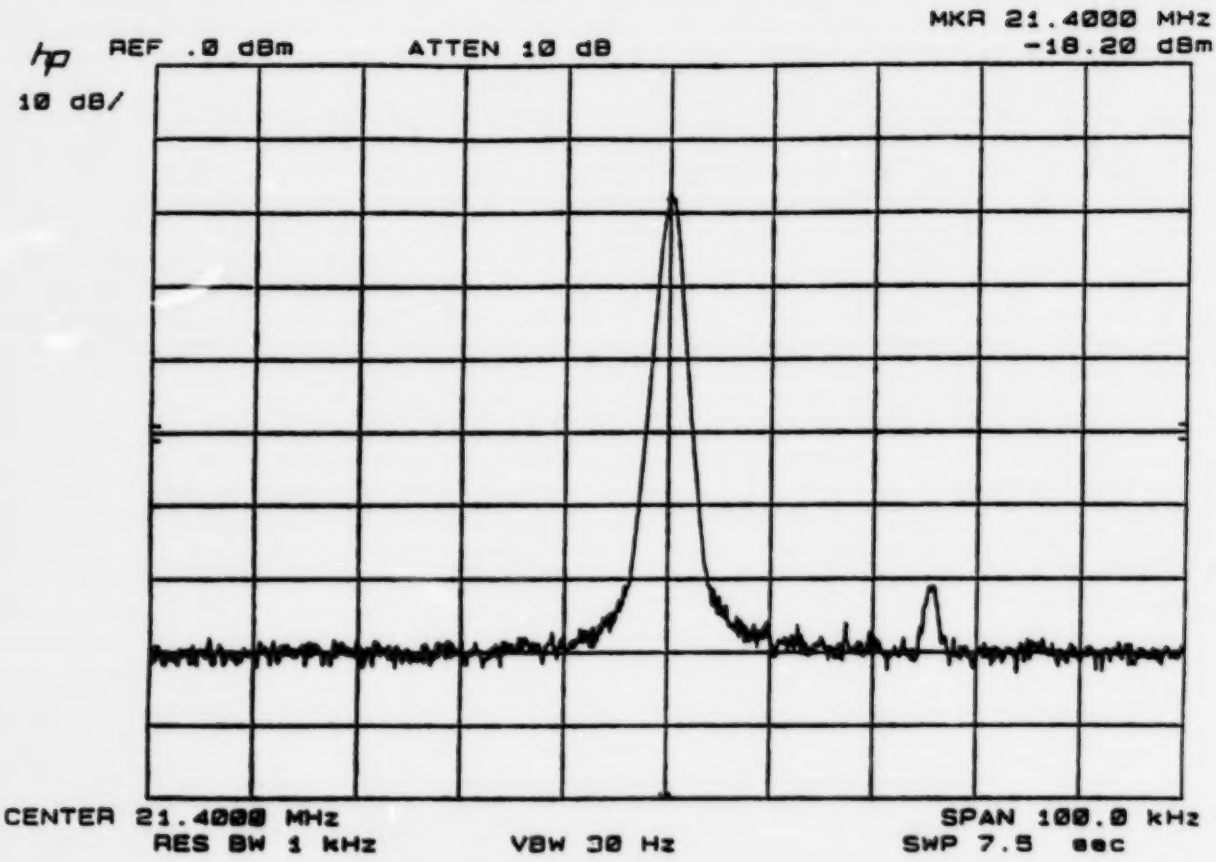

Fig. 12
"Switched IF Output" of WJ8617B Receiver Viewed With a Processing Gain of 36 dB

If one tone decreases in amplitude, it eventually falls below the noise floor of the receiver. When the lower signal plus noise-to-noise ratio is 3 dB, the lower signal is at the MDS level for the receiver. Therefore, MDS defines the lower bound of the IDR. The upper bound will depend upon whether AGC is present in the receiver or not.

In a receiver with AGC, the upper bound is given by the input signal strength for which the AGC starts to degrade the effective noise figure of the receiver. If the input signal is increased past this point the effective noise figure, defined by the ratio of the input SNR to the output SNR, will increase one dB for every dB the input signal increases. The increase in noise figure causes an increase in the MDS. The difference between the input signal strength and the MDS does not change. Therefore the IDR remains constant. It should be noted that AGC does not give a significant increase in the dynamic range of a wideband superheterodyne receiver as it did for the narrowband superheterodyne receiver. This is because of the degradation in receiver noise figure the AGC causes.

The point at which the degradation in noise figure starts is related to the 1 dB compression point of the amplifiers between the RF input and IF output. The degradation point could be increased by increasing the 1 dB compression point of the receiver front end. However, difficulties in the design of analog amplifiers with high 1 dB compression points may prevent this.

In a wideband superheterodyne receiver where AGC is not present, the upper bound of the IDR is given by the input 1 dB compression point.

Based on these bounds, the IDR can be defined by

$$IDR = S_u - MDS \tag{10}$$

IDR - Instantaneous Dynamic Range
S_u - Upper bound on input signal
For receiver with AGC - degradation point referenced to the input

For receiver without AGC - one dB compression point referenced to the input

Note that in the case of a wideband receiver without AGC, the Instantaneous Dynamic Range is the same as the Single Tone Dynamic Range that would be given by a narrowband superheterodyne receiver having the same resolution.

From equations 8 and 10 it can be seen that an increase in the IDR can be obtained by increasing the frequency resolution. Doubling the resolution results in a 3 dB increase in IDR. As in the case of the SFDR however, this small increase in IDR may not justify either the increase in complexity or the decrease in the probability of interception.

Instantaneous Dynamic Range is an imprecise parameter in that neither a one dB compression point, or an AGC degradation point is easily measured exactly.

Both the IDR and SFDR are functions of the noise figure and intermodulation characteristics of the receiver front end. They are also limited by the post processing employed. The lesser of the two, for a given wideband superheterodyne receiver, serves as a useful indication of the dynamic range performance of that receiver. The relationship between receiver noise figure, front end intermodulation characteristics, detection bandwidth, and processing gain must all be considered in the design of a wideband superheterodyne receiver.

5.0 DISCUSSION OF DREO WIDEBAND SURVEILLANCE RECEIVER

5.1 Introduction

Presently DREO is having a wideband superheterodyne surveillance receiver system built. The front end of the system will be a WJ8617B receiver. The 4 MHz "Switched IF Output" will be digitized by a Digital Quadrature Receiver presently under construction. This will provide the in phase (I) and quadrature (Q) components of the 4 MHz wide IF signal. A processor which will perform a complex FFT on the data will be built under a separate contract.

This wideband surveillance receiver will have two modes of operation, coarse search and fine search. In the coarse search mode a 4K FFT will be performed over the entire 4MHz IF bandwidth yielding a resolution of 1.5 kHz. In the fine search mode, the 4K FFT will be performed over a 200 kHz bandwidth giving a resolution of approximately 50 Hz. The processing time for the FFT will be 20 msec. In the coarse search mode therefore, the receiver will blink within a 4 MHz detection band and will sweep this detection band through the entire range of interest. In this case the frequency range of interest is confined to 20-1100 MHz due to the limits imposed by the tuning range of the WJ8617B receiver. In the fine search mode, double buffering of the 4K data points will allow the FFT to be performed without any data being lost. Therefore the receiver will effectively stare within the 200 kHz band. Assuming a filter settling time equal to $1/B_{det}$, a scanning narrowband superheterodyne receiver would require approximately 2 sec to perform an identical coarse search of a 4 MHz IF and at least 80 sec to perform an identical fine search of a 200 kHz band.

This section will examine the performance of the wideband system under development in terms of the dynamic range parameters introduced in the previous section. Measurements of the Spurious Free Dynamic Range and Instantaneous Dynamic Range were done on a WJ8617B receiver using an HP8568B spectrum analyser to simulate the processing gain of the coarse mode of the proposed FFT processor. A resolution bandwidth of 1 kHz was used on the spectrum analyser. The 1kHz resolution filter of the spectrum analyser actually has a noise power bandwidth of 1.2 kHz. As a result, a processing gain of 35 dB on the spectrum analyser was used to simulate the processing gain of 34 dB that the FFT processor will have. A processing gain of exactly 34 dB could not be simulated on the spectrum analyser. Also verification of the SFDR and IDR for the fine search mode could not be done because a 50 Hz resolution filter was not available on the spectrum analyser.

5.2 Processing Gain

Conceptually, the FFT can be viewed as a bank of narrowband resolution filters, each followed by an energy detector. Using this analogy, the processing gain for the coarse mode can be determined from equation 6:

B_{det} = 4 MHz

B_{res} = 1 kHz

P from equation 6 = 36 dB

For the fine search mode, equation 6 gives a processing gain of 49 dB. These figures represent upper limits to the processing gains. The values in the actual system will be somewhat less and will depend upon the type of windowing used and the amount of averaging.

5.3 Spurious Free Dynamic Range

The maximum spurious free dynamic range of the proposed system, operating in the coarse analysis mode can be predicted by using the following values in equations 7 and 9:

F = 10 dB

- measured value of noise figure for WJ8617B receiver.

B_{det} = 4 MHz

P = 34 dB

IIP = -53 dBm

- measured third order intercept point of WJ8617B receiver with AGC disabled and gain set to approximately 52 dB

MDS from equation 7 = -132 dBm

SFDR from equation 9 = 53 dBm

The predicted SFDR agrees quite closely with the value of 50 dB actually measured using the spectrum analyser.

This low SFDR seems due to the fact that the third order intercept point of the WJ8617B receiver used was not within specification. The IIP of -53 dBm measured would correspond to an OIP of -2.5 dBm. The specification for the third order intercept point quoted in the operator's manual is 3.0 dBm minimum [6]. This spec is presumed to be for the OIP which is independent of gain. Clearly, the spec was not met. This low OIP seems to be due to spurious signals which emanate from the logarithmic amplifier located beside the IF amplifier on the AM demodulator board. These spurious signals appear at the same frequencies as the third order products, but their behavior is not that of typical third order products. They do not increase 3 dB for a 1 dB increase in input signal strength. These spurious signals become very noticeable at low RF to IF gains or when the AGC is on. Tests made with other WJ8617B receivers revealed the same problem.

Performing the IIP measurements at the "Wideband IF Output" port of the WJ8617B resulted in a measured IIP of 7.7 dBm. The following values can now be used in equations 7 and 9:

$F = 10.0$ dBm

$B_{det} = 8$ MHz

$P = 10 \log(8 \text{ MHz}/1.5 \text{ kHz}) = 37$ dB

$IIP = 7.7$ dBm

yielding the following values: MDS = -132 dBm
SFDR = 93 dBm

While this SFDR could not be observed due to dynamic range limitations of the spectrum analyser, the SFDR was observed to exceed 80 dB.

These results indicate that superior SFDR performance for the coarse search mode of the proposed system might be achieved by using the "Wideband Output Port" of the WJ8617B receiver as the input to the digital post processor. The post processor will have an anti-aliasing filter of 4 MHz bandwidth, so the 8 MHz bandwidth of the "Wideband IF Output" would cause no aliasing problems. External gain as well as some external AGC would have to be added however, in order to bring the "Wideband IF Output" signal up to the same level as the "Switched IF Output". Since this external amplifier would provide most of the gain from RF to IF its intermodulation performance would govern that of the system. The third order intercept performance of this external amplifier would therefore have to be chosen carefully, or the SFDR would again suffer. It is doubtful that an amplifier providing the necessary gain and having an IIP of 7 dB could be found. However, it should not be difficult to find an external amplifier which would allow the IIP to be increased from -53 dBm.

The SFDR for the fine search mode can be predicted by substitution of the following values in equations 7 and 9:

$F = 10$ dB

$B_{det} = 8$ MHz

$P = 10 \log(4\text{MHz}/50\text{Hz}) = 49$ dB

$IIP = -53$ dBm

yielding MDS = -147 dBm
SFDR = 63 dB

5.4 Instantaneous Dynamic Range

In addition to the SFDR performance of the proposed system, the IDR must also be examined. Measurements of the effective noise figure performed on the WJ8617B indicate that for the "Switched IF Output" port (4 MHz BW), the AGC starts to degrade the effective noise figure for an input of approximately -55 dBm (Fig. 13). Using this value as S_u for equation 10 and an MDS of -132 dBm, the IDR for the surveillance system in the coarse search mode, is predicted to be 77 dB. The observed value, using a processing gain of 36 dB on the spectrum analyser, is 71 dB (Fig. 14). The error here can be attributed to the error in judging the correct value for S_u since the transition in Fig. 13 is not well defined. For the fine search mode of operation, the predicted value of IDR is 90 dB. This value could not be measured due to the fact that a resolution bandwidth of 50 Hz was not available on the spectrum analyser. It should be noted that if the separation of the two tones is less than 25 kHz, the phase noise of the local oscillator of the WJ8617B must come into consideration of the IDR. It is this phase noise which causes the skirts at the base of the signal in Fig. 14. The MDS must be redefined to be 3 dB above the level of the phase noise. This reduces the IDR. A separation of 50 kHz was used in Fig. 14.

5.5 Quantization

The estimates of SFDR and IDR quoted above were made with the assumption of infinite precision arithmetic. The system under development will have 9 bits of quantization. This will limit the dynamic range of the system to approximately 54 dB in either mode. This dynamic range, for the coarse search mode, is comparable to the SFDR of 53 dB quoted above. However, the system is being designed to enable more bits to be used as faster A/D converters with more bits become available. The dynamic range of the system, in coarse search mode, will then be limited by the SFDR of 53 dB quoted. As mentioned above, this figure could be easily increased through the use of an external amplifier and AGC. Assuming the external AGC will have a noise figure degradation point comparable to that of the AGC in the WJ8617B, a IDR of 77 dB will then limit the performance of the system in coarse search mode.

6.0 CONCLUSIONS

This report has examined dynamic range considerations in narrowband and wideband superheterodyne surveillance receivers. It has been seen that for a narrowband superheterodyne receiver, if proper design procedures are followed, the best indication of dynamic range performance is the Single Tone Dynamic Range. AGC can increase this performance. For the wideband superheterodyne receiver, the Single Tone Dynamic Range is an optimistic indication of the dynamic range performance. A more realistic indication is given by either the Spurious Free Dynamic Range or the Instantaneous Dynamic Range; whichever is less. In this case AGC has some benefits, but it does not result the same increase in performance as in the narrowband case due to the increase in noise figure it causes.

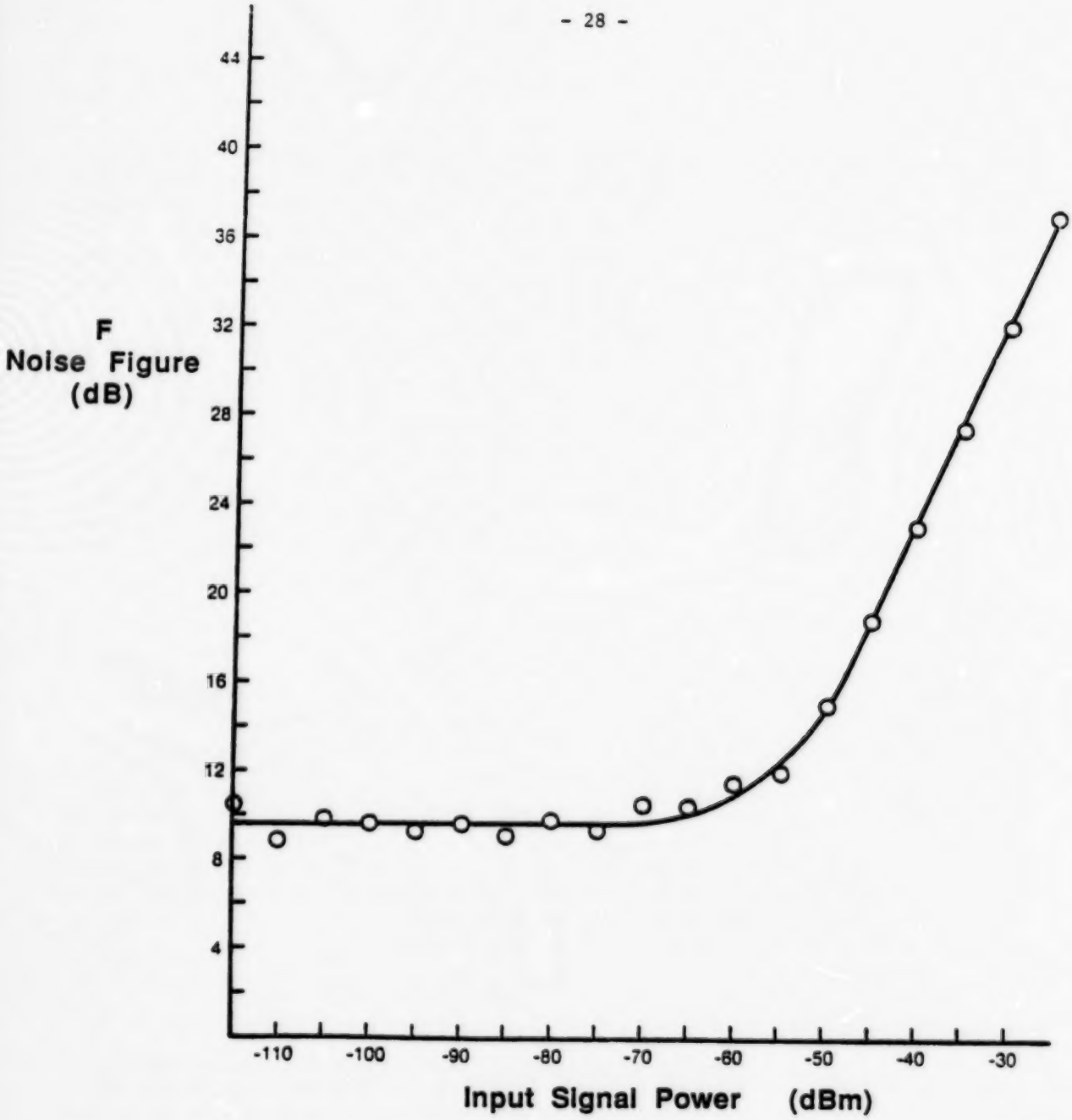

Fig. 13
Receiver Noise Figure Vs Input Signal Power
For WJ8617B Receiver
4 MHz BW, AGC On

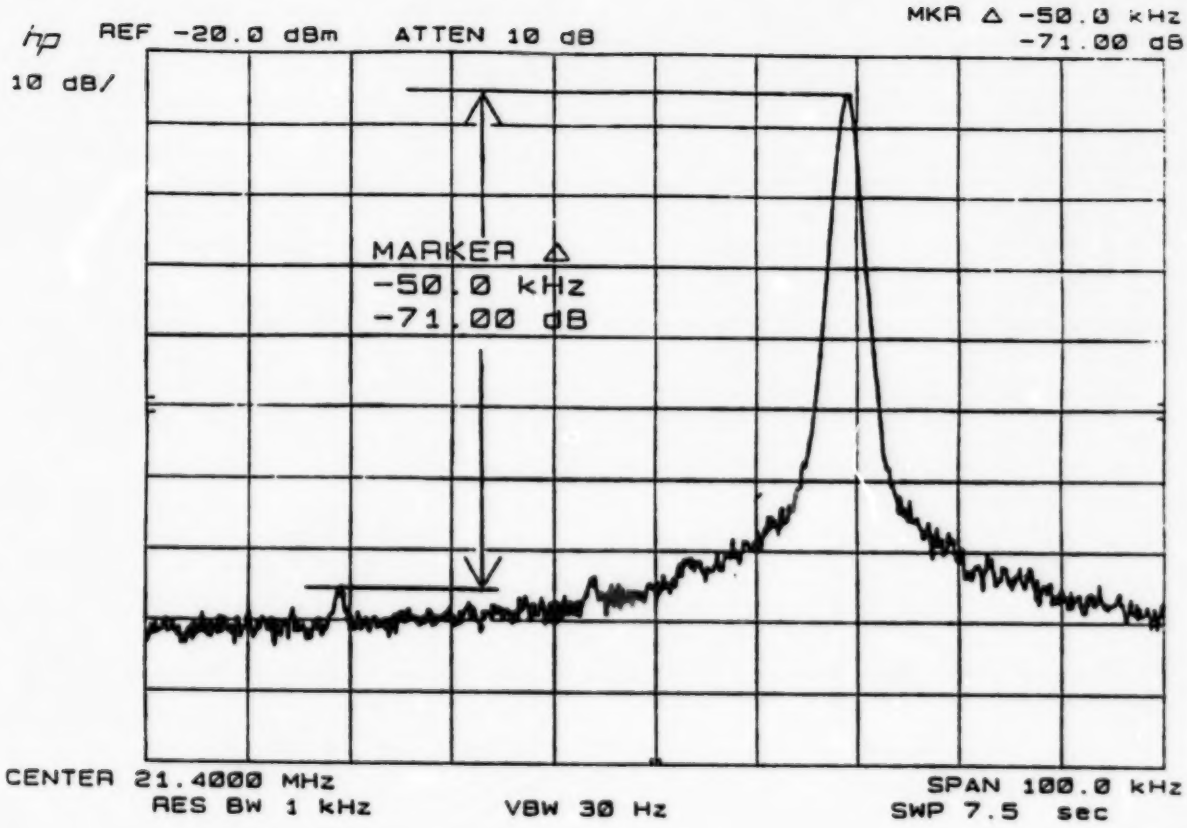

Fig. 14
IDR of WJ8617B Receiver
Viewed With a Processing Gain of 36 dB

The report also examined the impact of these dynamic range parameters on a signal surveillance system presently under development at DREO. The dynamic range of the proposed system, in the coarse search mode, will be limited by the SFDR of 53 dB. This is compatible with the 9 bits of quantization that will be provided. If a post processor becomes available which allows more bits to be used in the FFT, the SFDR of the system will have to be increased in order to take full advantage of the extra bits. This can be done fairly easily through the use of an external amplifier and AGC at the Wideband IF Output. The dynamic range of the coarse search will then be limited by the IDR of 77 dB, assuming that the point at which the external AGC will degrade the receiver noise figure is approximately equal to the noise figure degradation point measured in the WJ8617B receiver. It is not known if this degradation point could be improved. Improvements in the IDR and SFDR could be obtained by increasing the resolution, but this is very costly in terms of added complexity and a decrease in the probability of interception. They could also be increased by redesigning the receiver front end and increasing the IIP and AGC degradation point. This however may not be possible due to limitations in the state of the art in analog amplifiers. As a result, it may be quite difficult to obtain dynamic range performance better than 77 dB in the coarse search mode even if a post processor allowing more than 9 bits of quantization is found.

In the fine search mode 9 bit quantization will again limit the dynamic range to 54 dB. If more bits in the post processor stage become available, the dynamic range will be limited to a SFDR of 63 dB. If an external amplifier and AGC is used, the dynamic range of the fine search mode can be increased to 90 dB. To improve on this figure would require either a redesign of the front end or post processor.

7.0 REFERENCES

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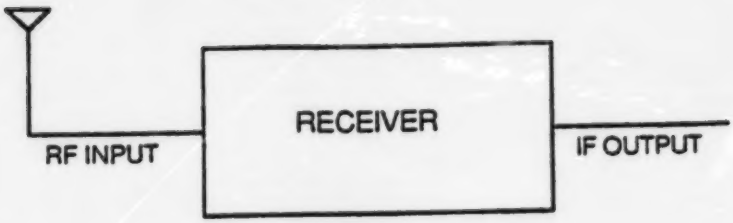
APPENDIX I

DERIVATION OF MDS



F - Receiver Noise Figure $\triangleq$ $\dfrac{\text{Input Signal to Noise Ratio}}{\text{Output Signal to Noise Ratio}} = \dfrac{SiNo}{NiSo}$

Minimum Discernible Signal (MDS) is defined as the input signal strength which causes a 3 dB signal plus noise to noise ratio at the IF output

$$\frac{So + No}{No} = 2 \qquad (3\ dB)$$

$$\therefore \quad \frac{So}{No} = 1$$

$$\frac{MDS}{Ni}\,\frac{No}{So} = F \qquad \therefore \quad \frac{MDS}{Ni} = F$$

$Ni = kTB_{det}$ - where B_{det} is the Effective Noise Bandwidth of the detection filter.

$$MDS = FkTB_{det}$$

Switching to dBm yields the following:

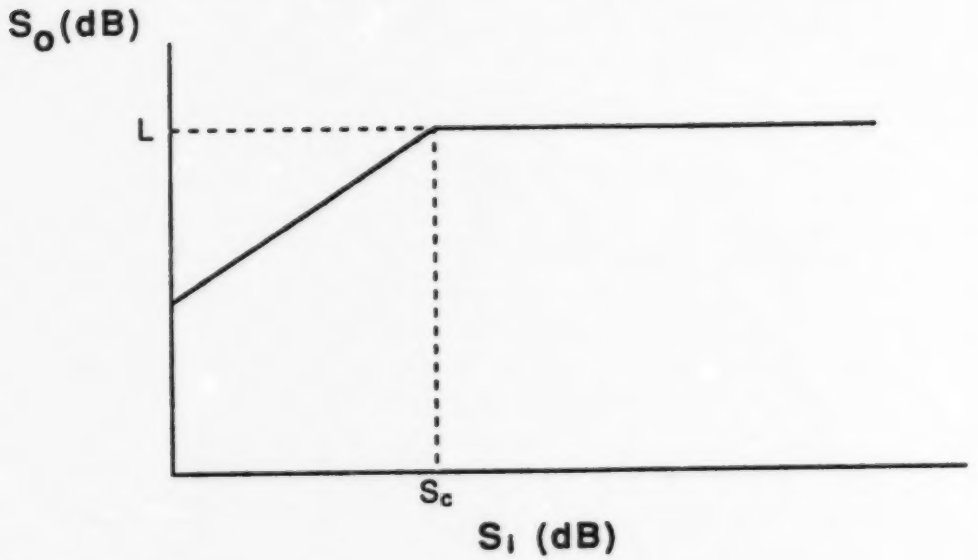
$$MDS = 10 \log [1000\ kTB_{det}]$$

APPENDIX II

DEGRADATION OF NOISE FIGURE

$$F = \frac{SNR_i}{SNR_o}$$

Assume an idealized transfer function similar to that shown below:



For $S_i < S_c$

This is the region whose noise figure measurements are typically done

$$F = \frac{S_i}{N_i} \frac{N_o}{S_o}$$

$$= \frac{S_i}{GS_i} \left[\frac{GN_i + N_r}{N_i}\right]$$

Nr - noise added by the receiver, referenced to the output.

It is assumed that Nr is constant and independent of gain.

$$F = \frac{GN_i + N_r}{GN_i}$$

$Ni = kTB_{det}$

$$F = \frac{GkTB_{det} + N_r}{GkTB_{det}}$$

For $S_i > S_c$

$S_o = L$

$$\frac{S_i}{N_i}\,\frac{N_o}{L} = F_{eff}$$ effective noise figure

$$L = S_c G \quad \frac{S_i}{KtB_{det}} \quad \frac{N_o}{S_c G} = F_{eff}$$

$N_o = GkTB_{det} + N_r$

kTB_{det} is still in the linear region of operation

$$\therefore F_{eff} = \frac{S_i}{kTB_{det}} \quad \frac{GkTB_{det} + N_r}{S_c G}$$

$$= \frac{S_i}{S_c} F$$

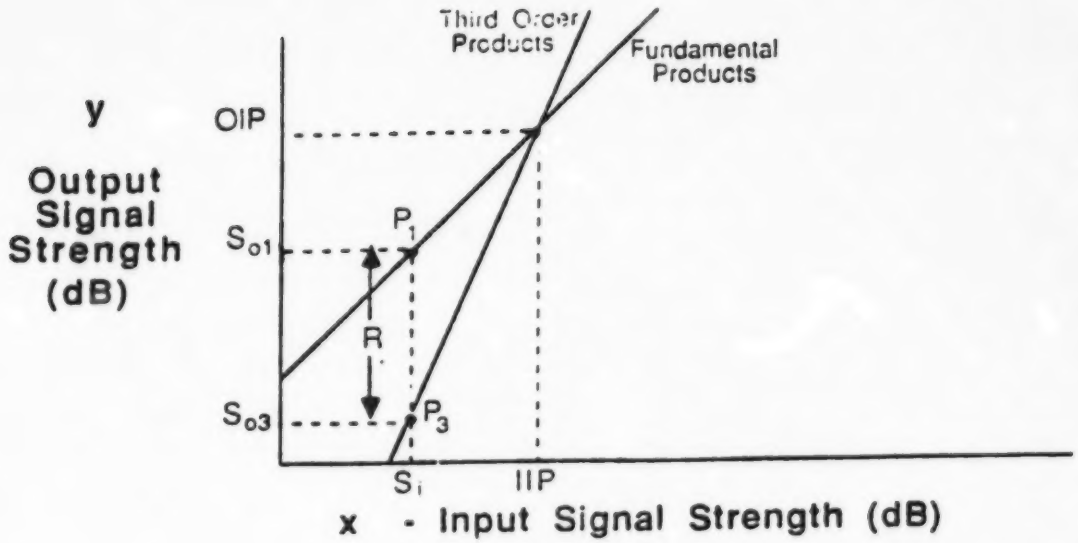
In dB notation

$$F_{eff} = S_i(dB) - S_c(dB) + F(dB)$$

$\therefore$ for $S_i > S_c$, the effective noise figure goes up dB for dB with input signal.

APPENDIX III

THIRD ORDER INTERCEPT POINT



The slope of the Fundamental Product Line is 1.
The slope of the Third Order Product Line is 3.

Using the slopes and two points (P1 and P3) an equation for each line can be found

Fundamental Product Line $y = x - S_i + S_{01}$

Third Order Product Line $y = 3x - 3S_i + S_{03}$

At the Input Intercept Point (IIP)

$$IIP - S_i + S_{01} = 3IIP - 3S_i + S_{03}$$

$$S_{01} - S_{03} \triangleq R$$

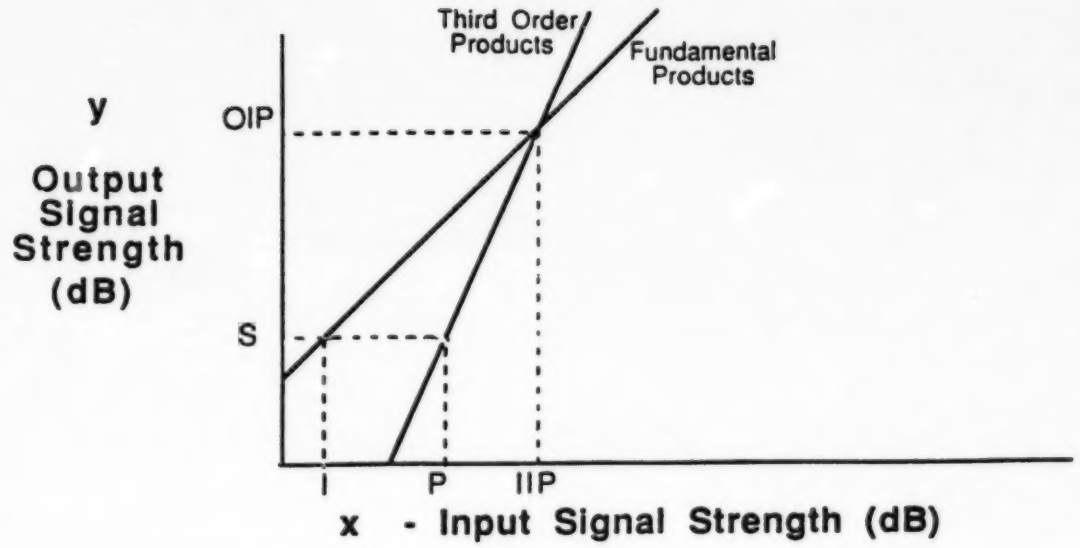
$$IIP = \frac{R}{2} + S_i$$

$$OIP = IIP + G$$

$$= \frac{R}{2} + S_i + G$$

APPENDIX IV

SPURIOUS FREE DYNAMIC RANGE



Along Fundamental Product Line $y = \chi + OIP - IIP$

Along Third Order Product Line $y = 3\chi + OIP - 3IIP$

Given a third order product of level S caused by an input signal of level P, it must be determined what the input signal level I would have to be in order to generate a fundamental product of level S.

$$S = 3P + OIP - 3IIP = I + OIP - IIP$$

$$I = 3P - 2IIP$$

U $\underline{\Delta}$ Upper Level of Spurious Free Dynamic Range

- level of two equal input signals necessary to create a third order product equal to the lower limit (L).

$$L = 3U - 2IIP$$

$$U = \frac{L + 2IIP}{3}$$

Spurious Free Dynamic Range

$$SFDR = U - L$$

$$= \frac{L}{3} + \frac{2IIP}{3} - L$$

$$= \frac{2}{3}(IIP-L)$$

L $\triangleq$ Lower Limit of SFDR = Minimum Discernible Signal (MDS)

$$\therefore SFDR = \frac{2}{3}(IIP - MDS)$$

*Taken from Ref. 5.

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